Enhancement of the field of first flux penetration due to Andreev bound states in Bi_2Sr_2CaCu_2O_8+delta

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Abstract

First flux penetration into single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$ is investigated using magneto-optical imaging and Hall probe array magnetometry. Below 50 K, a slight enhancement of the field of first flux penetration, H_p, is found when the edge normals are oriented at 45° with respect to the principal (ab) crystal axes, rather than parallel to them. We discuss this effect in terms of a role of Andreev bound states [1].

Key words: Surface Sheath, Vortex Lattices, First Flux Penetration, Surface Barrier, Andreev Bound States, d-wave Superconductivity
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In superconductors with dominant $d_{x^2-y^2}$ symmetry of the gap function [2], Andreev bound states are predicted to occur at surfaces that are perpendicular to the gap node direction [3, 4, 5]. In $Bi_2Sr_2CaCu_2O_{8+\delta}$, this corresponds to a surface normal at 45° with respect to the (a, b) axes. The quasiparticle current carried by the bound states in response to the application of an external magnetic field H_a is expected to partially compensate the Meissner current, thereby increasing the Bean-Livingston (BL) barrier [1] and the field of first flux penetration H_p.

We search for this effect in optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals ($T_c = 88$ K) grown by the travelling solvent floating zone technique. A large crystal, the orientation of which is known from the X-ray precession method, is selected using the magneto-optical imaging (MOI) technique [7]. From this, successive squares of aspect (thickness/width) ratios d/w ranging between 0.045 and 0.47 are cut using a wire saw with 1 μm SiC grit. At each stage, H_p is measured using MOI. The local image intensities are calibrated and transformed to maps of local perpendicular magnetic induction $B^{\perp}$. From these, loops of the local hysteretic self–field $(B^{\perp} - \mu_0 H_a)$ are obtained, on which the field of first flux penetration appears as a sharp minimum [8], see Fig. 1. Similar curves are obtained from Hall array magnetometry. Thus, we establish the dependence of H_p on the thickness-to-width ratio d/w for square superconducting samples (of rectangular cross-section).

The H_p^0 values for five squares with the edges $\|$ a, b, and the value of H_p^{45} for the single square (with $d/w = 0.12$) that has the edges oriented at 45°, are collected in Fig. 2, for different temperatures. The dependence of H_p on (d/w) follows that expected for the relevant case of a superconductor of rectangular cross-section[8],

$$H_p = H_p^{\infty} \tanh\left(\sqrt{\beta d/w}\right). \quad (1)$$

The prefactor extracted from fits of the data in Fig. 2 to Eq. (1) corresponds to the penetration field in the limit $d/w \to \infty$. Its experimental temperature dependence, shown in Fig. 3, follows that expected for the superfluid density of a d-wave superconductor [9], with the $T \to 0$ extrapolated value $H_{c1}(0) = 180$ Oe. The experimental value of β, plotted in the inset to Fig. 3, is temperature dependent. It does not correspond to that expected for the infinite strip, $\beta = 0.36$ [8], but depends on the crystal shape as well as on the rate of thermally activated vortex entry into the $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal [10]. This is determined by the activation of individual pancake vortices over the BL barrier at the lateral crystal edges.

Fig. 2 shows that for $T < 50$ K, H_p^{45} lies above the fit of H_p^0 to Eq. (1). Above 50 K, the geometrical barrier [8] limits flux penetration; the BL barrier is ineffective and no enhancement is observable. Below 50 K, flux entry is opposed by the BL barrier; we find H_p^{45}/H_p^0 to be enhanced up to a factor 1.25 when the edge normals are parallel to the gap nodes.

In summary, we establish the dependence of the field of first vortex penetration H_p on the thickness-to-width ratio in square superconductors of rectangular cross-section. The numerical relation between H_p and the first critical field H_{c1} depends sensitively on

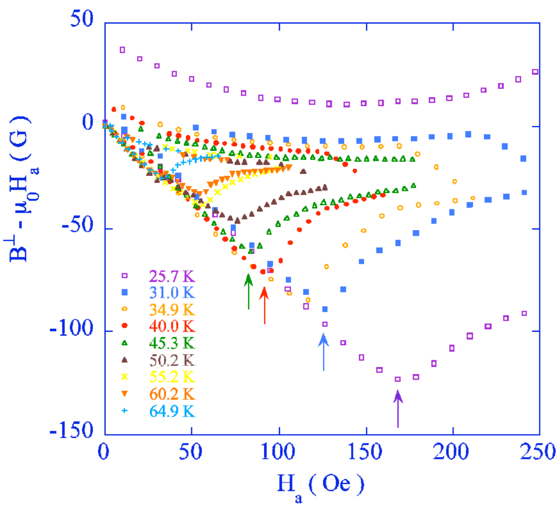

Figure 1: Hysteresis loops of the self-field at different temperatures, extracted from MOI of flux penetration into the crystal with edges oriented at 45° with respect to a, b after zero-field cooling. The H_p-values for the lower temperatures are marked with arrows.

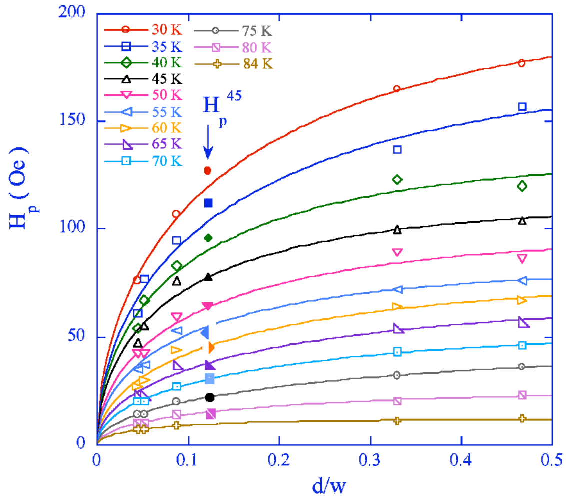

Figure 2: H_p as function of aspect ratio d/w, for the series of square crystals with the edges $\|\ a, b$ (open symbols) and at 45° (closed symbols). Drawn lines are fits to Eq. (1).

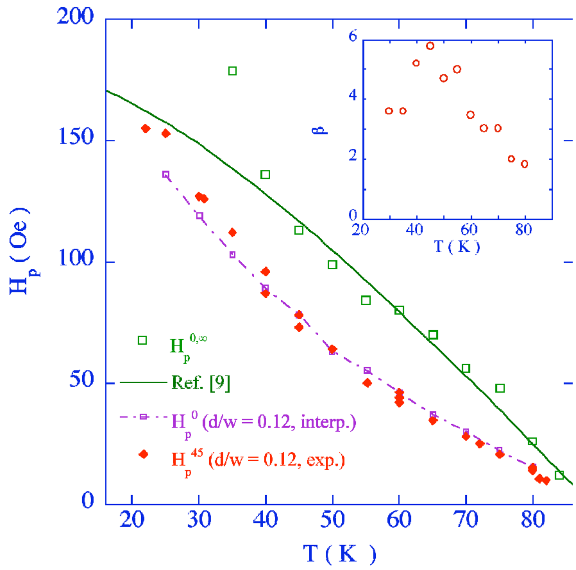

Figure 3: (a) $H_p^{0,\infty}$ extracted from the fits to Eq. (1) in Fig. 2, together with the experimental H_p^{45}-data (for $d/w = 0.12$), and the values of H_p^0 expected or the same aspect ratio. (b) $\beta(T)$, from the fits to Eq. (1) in Fig. 2.

sample shape and on thermal activation of vortices over the surface barrier [10]. In the d-wave layered superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$, H_p below 50 K is enhanced when the normals to the lateral crystal edges are oriented along the gap nodes. We attribute this effect to the anisotropy of the Meissner current due to the presence of Andreev bound states [1].

References

[1] C. Iniotakis, T. Dahm, and N. Schopohl, Phys. Rev. Lett. **100**, 037002 (2008).

[2] J.R. Kirtley, C.C. Tsuei, H. Raffy, Z.Z. Li, A. Gupta, J.Z. Sun, S. Megtert, Europhysics Lett. **36**, 707 (1996).

[3] C.R. Hu, Phys. Rev. Lett. **72**, 1526 (1994).

[4] Y. Tanaka and S. Kashiwaya, Phys. Rev. Lett. **74**, 3451 (1995).

[5] S. Kashiwaya and Y. Tanaka, Rep. Prog. Phys. **63**, 1641 (2000).

[6] M. Li, P.H. Kes, S.F.W.R. Rycroft, C.J. van der Beek, and M. Konczykowski, Physica C **408-410**, 25 (2004).

[7] L.A.Dorosinskiĭ, M.V. Indenbom, V.I. Nikitenko, Yu.A. Ossip'yan , A.A. Polyanskii, and V.K. Vlasko-Vlasov, Physica C **203**, 149 (1992).

[8] E.H. Brandt , Phys. Rev. B **60**, 11939 (1999).

[9] R.J. Radtke, V.N. Kostur, and K. Levin, Phys. Rev. B **53**, R522 (1996).

[10] N. Chikumoto, M. Konczykowski, N. Motohira, and A.P. Malozemoff, Phys. Rev. Lett. **69**, 1260 (1992).

[11] L. Burlachkov, V.B. Geshkenbein, A.E. Koshelev, A.I. Larkin, and V.M. Vinokur, Phys. Rev. B **50**, 16770 (1994).
S. Kashiwaya and Y. Tanaka, Rep. Prog. Phys. 63 1641 (2000).